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Microburst Damage Assessment and Forest Composition Reconstruction After Hurricane Isabel in the College Woods, Williamsburg, VA

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ABSTRACT PAGE

Hurricane Isabel hit the Williamsburg, VA, region on September 18, 2003, as a Category 2 storm. In addition to damage from general hurricane winds, the storm produced a multi-hectare microburst in the College Woods Research Preserve of the College of William and Mary. None of the permanent plots in the preserve were located within this severely damaged microburst area. For this study, permanent plots were set up in both the microburst area and an immediately adjacent less disturbed reference area. All trees ≥ 5 cm diameter at breast high (dbh) located within the plots were identified, whether standing or lost, and the nature of damage recorded. A total of 1106 trees ≥ 5 cm dbh were recorded, with 535 in the reference area and 571 in the microburst area. Relative density, basal area, and importance values were determined for each species. Rank in abundance and basal area were not the same in the reconstructed vegetation of the reference and microburst areas, despite their adjacency. Therefore, the lack of salvage logging that allowed reconstruction of the pre-hurricane damage was essential in getting an accurate measure of actual damage and loss. Among trees ≥ 10 cm dbh, nearly all species were significantly more likely to be damaged or lost in the microburst area than in the reference area. Among these, *Quercus rubra* sustained significantly more damage and stem loss than expected based on frequency of damage and loss in all species combined in both the reference and microburst areas, the only species to do so in the reference area. *Quercus alba*, *Liriodendron tulipifera*, and *Oxydendron arboreum* showed significantly more damage and stem loss than expected in the microburst area, while *Ilex opaca* showed significantly less damage and stem loss and *Fagus grandifolia* also had less stem loss than expected. For trees < 10 cm dbh, *Cornus florida* showed significantly more damage and stem loss than expected in the microburst area based on frequency of damage and loss in all small trees combined, while *I. opaca* and *Liquidambar styraciflua* showed significantly less damage than expected in the microburst area. In the microburst area, but not in the reference area, there was a significant correlation between size class and percent damaged, size class and percent lost, and size class and percent uprooted. Larger trees were more likely to suffer direct wind damage, while smaller trees tended to suffer secondary damage from falling nearby larger trees. Some trees considered lost were able to resprout in the first year or two after falling, but none of these sprouts survived beyond the fifth year.

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Dedication

For Carl

Acknowledgements

I would like to thank my advisor, Dr. Ware, for his tireless work and guidance throughout all stages of this project, from field work to manuscript preparation. I would like to thank my committee members Dr. Case and Dr. Fashing for their input, help, and advice for making this manuscript better. I would also like to thank my husband Carl for his map-making, editing, and formatting skills, as well as his support for and patience with all aspects of this project.

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Introduction

Hurricanes affect many different regions of the world and damage many different ecosystems. They are particularly destructive to forest ecosystems. Hurricane disturbance can cause shifts in the structure of a forest, affecting not only the present species composition but the future composition as well (Foster 1988, Greenberg and McNab 1998). In regions that do not experience frequent fires, hurricanes may fill the disturbance niche by initiating species change in forests (Canham and Loucks 1984). According to Gresham *et al.* (1991), high hurricane frequency may have determined the dominant tree species in coastal southeastern United States forests through selection of a suite of hurricane-resistant trees.

Wind disturbance in forests and forest response

Magnitude, intensity, and severity are important factors in determining damage caused by wind disturbance (Webb 1999). Windstorm magnitude is how wide the damage extends in an area, intensity is defined as the storm's force, and severity is the amount of change to an ecosystem caused by the windstorm (Webb 1999). The intensity, and thus the severity of hurricanes hitting Virginia has generally been less than in other southeastern states (Prengaman *et al.* 2008). Hurricanes typically make landfall further south, and while causing heavy rains and flooding in Virginia, their strongest winds usually affect only coastal forests in Virginia. In contrast, Hurricane Isabel in 2003 was a very large storm that was still quite strong as it passed northwestward from coastal North Carolina across central Virginia and into Maryland (Prengaman *et al.* 2008).

There are various responses of forests to wind disturbance (Webb 1999). Response to disturbance may be an increase in diversity, maintenance of current composition, or a loss of diversity (Webb 1999). The recovery from small-scale, less severe disturbances is usually through the growth of already established saplings and seedlings, as well as the growth of branches on nearby larger trees. Conversely, the recovery from large, more severe disturbances generally involves ecological succession (Runkle 1985).

The rate of tree death from wind damage can influence which species are found in a forest (Runkle 1985). Wind disturbance not only controls immediate post-hurricane composition but may play a role in determining future forest structure and composition. For example, small trees can benefit from gaps created by wind disturbance. Tree-fall allows surrounding plants to utilize resources such as moisture and nutrients that were previously used by the particular tree. Decreased below-ground competition from nearby roots also increases the chance of survival of some seedlings (Webb 1999).

Susceptibility to damage

The fate of individual trees in a windstorm is very difficult to predict, as there are many variables that play a role in a particular tree's susceptibility to wind damage. Trees that were not previously exposed to strong wind may show increased damage (Spatz and Bruechert 2000). On the other hand, trees that remain standing following wind disturbance may become more susceptible to later windstorms. Although they may have survived the major wind event, future wind may cause increased damage due to a new exposure from the loss of surrounding vegetation. Additionally, trees damaged in previous wind disturbances may be more susceptible to uprooting, especially if the wind is in a different direction than the previous event (Putz and Sharitz 1991, Everham and Brokaw 1996).

The term "damage" includes loss of major limbs and similar effects that do not kill the tree, as well as actual loss of a tree from the forest through death and decay. Loss can occur by either uprooting or breaking of the trunk. Uprooting occurs when the forces applied to the crown of the tree are greater than the strength of the force holding the roots in the soil but do not break the stem (Putz *et al.* 1983). Trees break off when the force applied is stronger than the stem strength but not strong enough to break and dislodge the roots (Putz *et al.* 1983). Most studies of the effects of hurricanes on forests focus more on tree loss than on crown breakage, since it is tree loss that has the most ecological effect on forests.

Previous studies have shown a positive linear relationship between stand age (in even aged stands) and damage inflicted by a hurricane, as well as between height and damage in all forests (Foster 1988, Foster and Boose 1992, Martin and Ogden 2006). Height, however, appears to be a better predictor of wind damage than age (Martin and Ogden 2006). Taller trees are generally more susceptible, although with tall trees both weight and crown size (see below) may also play a role (Webb 1999). Trees with larger diameter at breast height (dbh) often suffer more damage than smaller trees (Gresham *et al.* 1991). Putz *et al.* (1983) found that trees with larger dbh were more likely to be uprooted than smaller trees, which suffered more snapping. Shorter trees are also susceptible to damage, however, as they can be broken or crushed by falling tall trees (Webb 1989, Webb 1999, Prengaman *et al.* 2008). In contrast, other studies have found no clear relationship between tree size and damage or loss (Putz and Sharitz 1991, Matlack *et al.* 1993, Zimmerman *et al.* 1994). However, other studies found that size seemed important in determining damage and loss for some species but not all (Greenberg and McNab 1998, Webb 1989).

In addition to height and trunk size, other morphological characteristics may influence susceptibility to wind damage. For example, root systems play a role in damage resistance, as trees with shallow roots are more susceptible to damage (Gresham *et al.* 1991). Crown size and shape can determine how much stress is placed on the stem and roots of a tree (Mergen 1954, Putz *et al.* 1983). Prengaman *et al.* (2008) found that trees with larger crowns are more susceptible to uprooting than those of equal height but with smaller crowns.

The timing of wind disturbance in forests may also play a role in determining the amount of damage. For example, in winter, deciduous trees have no foliage, reducing wind drag on the crown, and frozen soil may provide more anchorage for root systems (Everham and Brokaw 1996).

Wood strength is also an important factor in determining potential damage. Wood density and strength have been shown to be greater for uprooted versus snapped trees, while wood elasticity is less for uprooted trees (Putz *et al.* 1983). Since wood strength, like final height and crown shape, differs among tree species, different tree species have different levels of susceptibility to wind damage. Species with weaker wood are generally more susceptible to overall damage (Webb 1989, Webb 1999). Some studies have found that conifers are more susceptible to general wind damage than hardwoods (Foster 1988, Foster and Boose 1992), while others have found the opposite (Gresham *et al.* 1991). Large trees that lose branches or large portions of their crowns early in a storm may be able to avoid more severe damage, like broken trunks or uprooting, because branch and foliage loss decreases wind resistance (Putz *et al.* 1983, Putz and Sharitz 1991). In fact, wind storms that reach their maximum speed quickly may cause more damage as there is not enough time for defoliation (Francis and Gillespie 1993).

The particular forest environment may also influence individual tree damage. A negative relationship has been found between tree density and damage (Foster 1988). Also, forests that have been thinned or otherwise managed tend to be more susceptible to damage (Foster 1988). In addition, soil depth may play a role in the susceptibility of trees to wind damage. Trees found on shallow soil may have greater likelihood of uprooting as opposed to breaking (Foster 1988).

Microbursts

During a hurricane, other wind events besides the general hurricane winds may develop, increasing damage levels. For example, sudden local downbursts of air may occur, causing severe localized damage. Microbursts are a category of downbursts that extend horizontally up to 4 km, and sustain wind speeds up to 92 m/s. Speeds such as this have been shown to remove up to 70% of canopy cover in forests (Peterson 2000a, Foster 1988). Microbursts are divided into "dry" and "wet" events. "Dry" microbursts do not involve precipitation that reaches the ground, while "wet" microbursts do occur with this precipitation (Caracena *et al.* 1989, Peterson 2000a). Microbursts are generally short-lived, rarely lasting more than 10 minutes (Peterson 2000a). The downburst winds may also increase in strength once they have come into contact with the ground (Peterson 2000a).

The mechanisms behind microbursts are poorly understood, and few studies have focused on the damage they cause. Unlike other hurricane damaged areas, spatial aspects and sizes of microburst areas have rarely been quantified (Peterson 2000a). In fact, microbursts were not recognized as separate events from tornadoes until the 1970s (Frelich and Lorimer 1991). This may be due to the fact that microbursts often occur during the same storm event as tornadoes, occurring to the right of the tornado's path (Peterson 2000a). Damage from these two types of storms can be distinguished by the consistent single direction of tree fall in microbursts compared with multi-directional tree fall caused by the swirling winds of tornadoes (Peterson 2000a).

When Hurricane Isabel struck forests in the Williamsburg, Virginia area in 2003, there were local areas of very severe damage apparently created by intense westward-moving downdrafts (downbursts or microbursts). These areas tended to have distinct boundaries, with most trees having been uprooted within these boundaries. The relatively few trees remaining upright in these areas sometimes had lost large branches, but defoliation of these standing trees was not pronounced (Prengaman *et al.* 2008).

While the magnitude of microburst damage was small compared with that of general hurricane winds, both the intensity and severity were obviously much greater in the microbursts. None of the permanent plots examined after the hurricane by Prengaman *et al.* (2008) were fully in the microburst areas, so their conclusions about storm damage were based largely on effects of general hurricane winds. They were unable to assess the amount of damage and tree loss within microburst areas during Hurricane Isabel.

Salvage logging

Following severe wind disturbance, forests are often salvage logged to save usable wood and to reduce future fire potential, because the more woody debris in a forest, the greater the risk of fire (Everham and Brokaw 1996). Many previous studies of wind-damaged ecosystems have had to gather data from forests that had already been salvage-logged, which can dramatically alter both immediate and future forest composition and structure, even delaying recovery (Elliott *et al.* 2002, Lindenmayer *et al.* 2004, Rumbaitis-del Rio 2006). Stumps and fallen trees may also sprout, which can not happen if the tree is removed by salvage logging (Webb 1999). Salvage logging also removes potential nutrient sources. Fallen trees that have died decompose and release nutrients back into the surrounding environment, which may then be utilized by other plants (Webb 1999).

Another important advantage of not salvage logging is that pre-disturbance reconstruction of the forest may be possible. Where wind disturbance will occur is not predictable, making it difficult to set up study plots prior to the disturbance so that pre- and post-disturbance composition may be compared. The lack of knowledge of pre-disturbance forest composition hinders the study of wind damage (Cooper-Ellis *et al.* 1999, Webb 1999). Webb (1999) claims that in order to accurately study wind damage in forests, salvage logging needs to be avoided. Thus, when the forest is left alone following wind disturbance, pre-disturbance composition may be inferred by cataloging all trees, both standing and fallen.

Study description

The purpose of this study was to document wind damage to an old (150+ years) North American temperate hardwood forest caused by a hurricane. More specifically, it was to compare damage in a microburst area and a nearby, less disturbed area affected only by general hurricane winds. In addition, pre-disturbance species composition of the forest was reconstructed, made possible only because the Williamsburg, Virginia study site had not been salvage-logged.

Materials and Methods

The hurricane and the study site

On September 18, 2003, Hurricane Isabel made landfall in North Carolina as a Category 2 hurricane (Beven and Cobb 2004). The storm then moved northwestward across southern and central Virginia, eventually weakening to a tropical storm near the Maryland border. The eye passed within 130 km of our study site in Williamsburg, Virginia (Prengaman *et al.* 2008). During this storm, the City of Williamsburg received 4.5 inches (11 cm) of rainfall. At Gloucester Point, VA, approximately 15 miles (24 km) farther away from the hurricane's eye than Williamsburg, peak sustained winds were measured at 60 knots (31 m/s), with gusts up to 79 knots (41 m/s) (Beven and Cobb 2004). Hurricane Isabel was the first major hurricane to hit the Williamsburg area in at least 75 years (Prengaman *et al.* 2008).

The College Woods (a.k.a. Matoaka Woods) is a 600 hectare research preserve on the campus of the College of William and Mary located in Williamsburg, VA. When Hurricane Isabel hit the College Woods, it not only caused damage from general hurricane winds, but also produced a multi-hectare highly damaged microburst area. The microburst area covered 3.47 hectares of forest (K. Prengaman, personal communication). The microburst winds were from the east, indicated by the highly consistent westward direction of tree-fall in this area.

The specific area that contains the microburst damage is located on "Squirrel Point", a peninsula extending into Lake Matoaka (Figure 1). This area of the woods is an approximately 150-year old temperate hardwood forest (Kribel 2003, Prengaman *et al.* 2008, Kribel *et al.* 2011). Common overstory tree species in this area include *Liriodendron tulipifera*, *Quercus alba*, *Fagus grandifolia*, *Quercus rubra*, and *Quercus falcata*. Understory trees include *Ilex opaca*, *Fagus grandifolia*, *Acer rubrum*, *Cornus florida*, and *Nyssa sylvatica*.

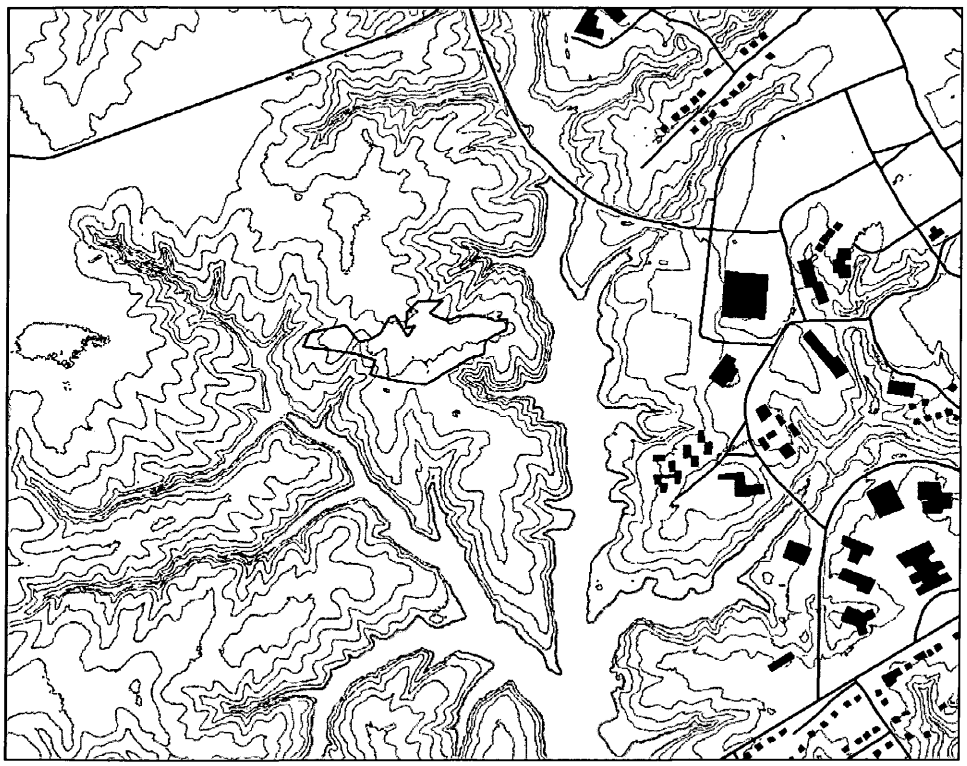

Figure 1. Location of microburst area in College Woods, Williamsburg, VA, outlined at left center, between two main arms of Lake Matoaka.

Plot locations

In order to document damage done by the microburst and allow monitoring of post-hurricane recovery, permanent plots were set up both within the microburst area and the immediately adjacent reference area. A 10m by 10m grid system was superimposed over both the microburst and reference area and used to determine the placement of the plots. This was utilized to avoid haphazard or potentially biased placement of plots within the microburst area. Each sampling plot was 20m x 20m, encompassing four 10m x 10m grid squares (400 m^2). The edges of plots were usually 10 m apart along the north-south axis, and 20 m apart along the east-west axis, although occasional shifts of 10 m were necessary on the east-west axis to fit the plots inside of the microburst boundaries (Figure 2). Eighteen 20m x 20m plots were fitted into the microburst area. All plots were entirely inside the microburst area proper, and did not contact the edge of the microburst area or the cleared walking trail running down the center of the microburst area. This was done to ensure that the data collected were from the most heavily damaged microburst area proper, and not the zone of moderate damage that encircled the microburst.

Plots were also established on the grid pattern in the reference area. These plots were also set up 10 m apart along the north-south axis, and 20 m apart along the east-west axis. As in the microburst area, eighteen plots were set up in this reference area. In both the microburst and reference areas, plots were on level to gently sloping ground so potential effects of steep slope on wind damage were avoided (Schaetzl *et*

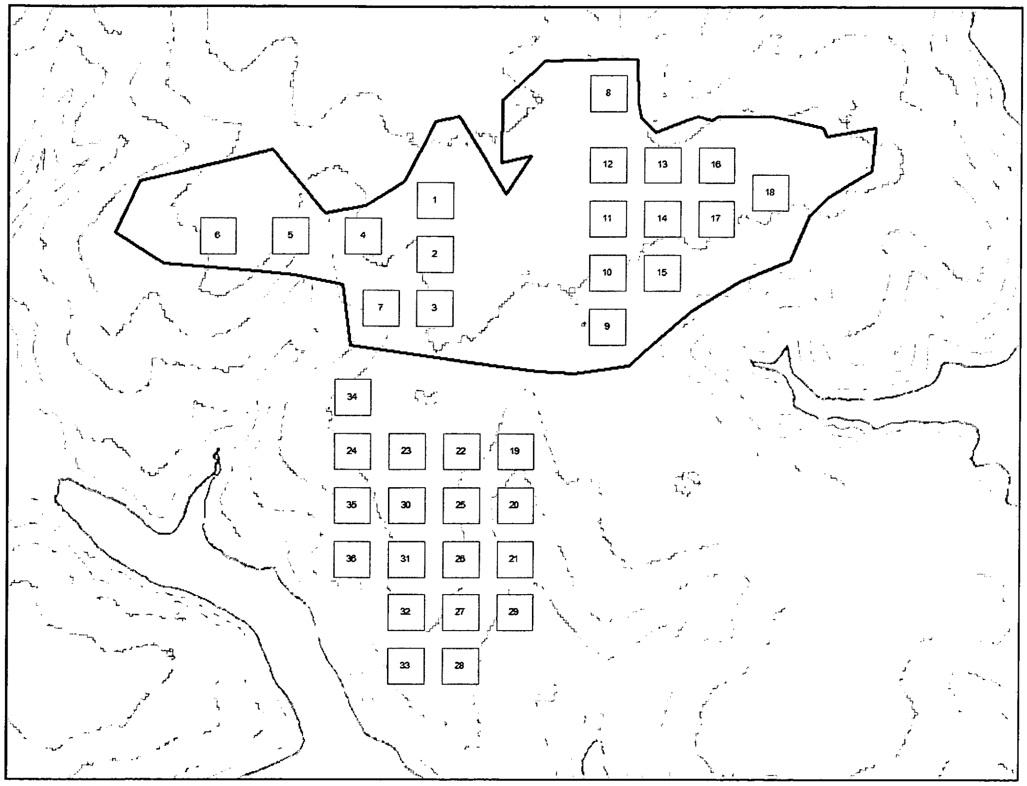

Figure 2. Schematic of plot locations in reference and microburst areas. No plots were set up in the center of the microburst due to a foot path running through this area. Contour lines represent 10 ft intervals.

al. 1989, Foster and Boose 1992, Everham and Brokaw 1996, Prengaman *et al.* 2008).

Grid and plot set-up

During grid and plot set-up, the dense tangle of fallen tree trunks and tree crowns made stretching a measuring tape between grid corners impossible. A sighting instrument was therefore necessary for determining distances through the dense tree debris. Therefore, a Spiegel Relaskop was used to sight out grid sides and corners, and a Brunton pocket transit was used to determine the angle of the sighted lines.

The dense foliage of understory trees and shrubs growing rapidly in response to an open canopy in the microburst area often made establishing a line of vision through the vegetation difficult. To create a more conspicuous sighting target, a piece of bright pink paper was affixed to the back of a clipboard. The paper had a width that, when viewed through the Relaskop at a distance of ten meters, would fit exactly between two vertical lines on the Relaskop screen. The 10m grid lines were surveyed and marked using the Relaskop and this bright pink sighting target. The line of sight along some grid lines was so obscured by dense vegetation that these lines had to be indirectly established. This was done by locating each end of the inaccessible line by sighting along perpendicular grid lines.

Plastic coated round metal garden stakes were used to mark the location of each plot. Stakes were placed at each corner of each 10m x 10m square. Each 20m x 20m plot therefore had 9 stakes (four 10m x 10m squares). Orange flagging was tied near the top of each stake, labeled with the plot number, and specific stake name for that plot (NE corner, NW corner, center, etc.). Tall stakes (4 ft) were used in the microburst area, as the vegetation and tree debris made shorter stakes extremely difficult to see. Shorter stakes (2 ft) were used in the reference area, as visibility was not a problem. GPS data were collected from the center stake of each 20 x 20 m plot using a Garmin E-trexVista GPS unit. These data points were used to create a map of the plot locations.

Data collection

Diameter at breast height (dbh) was measured for all trees larger than 5 cm dbh using a diameter tape. Previous post-hurricane studies have used 5 cm as the minimum size of trees measured (Foster 1988, Boucher *et al.* 1990, Merrens and Peart 1992, Cooper-Ellis *et al.* 1999), since finding and measuring all crushed stems smaller than that is considered impractical. Breast high was defined as 1.4 m high, as this is a common height used in other studies (King 1986, Frelich and Lorimer 1991, Matlack *et al.* 1993, Peterson 2000b). For uprooted or otherwise leaning trees, measurements were taken 1.4 m along the trunk from where the soil line would have been if the tree were still upright. If this exact location was not accessible because the stem was buried under another fallen tree, measurements were taken slightly above breast high to avoid inflating biomass by measuring below breast high. When this was necessary, it was noted in the data collected. Sometimes using a diameter tape was not possible, such as when the lower trunk of an uprooted tree was flush against or slightly sunken into the ground. In those cases a set of large calipers constructed specifically for this study was used to measure the diameter.

Trees were identified using leaves and bark on live trees, while bark and twig characters were used for dead trees. This was possible as the bark was still on the trees and had relatively little insect damage. Any tree that was already missing large amounts of bark, or showed extensive insect or rot damage was assumed to have died or been damaged prior to the hurricane. Nomenclature follows Radford *et al.* (1968) except his *Carya ovalis* was treated as *Carya glabra* var. *ovalis*.

There were no significant disturbances in the forest between Hurricane Isabel and the sampling. Tropical Storm Ernesto moved through the region in August 2006, before all data were collected, and a nor'easter struck two weeks later in early September. Each storm caused a few additional trees in the microburst area to fall, likely because individuals in this area were weakened by Hurricane Isabel and the increased exposure following the hurricane. Previous studies have found increased damage to trees that had been damaged by earlier storms (Mergen 1954, Putz and Sharitz 1991, Everham and Brokaw 1996). New damage from these storms, however, was easily recognized and differentiated from damage done earlier by Hurricane Isabel.

Damage assessment

In addition to diameter, degree of damage was noted for each tree larger than 5 cm dbh. Trees were classified into one of seven non-overlapping damage categories: uprooted, crushed, snapped off, bent, leaning, broken, and undamaged (all defined below). Similar damage categories have been used in previous studies, such as Cooper-Ellis *et al.* (1999) and Lafon (2006). How much of a tree crown was lost, such as missing branches or the whole crown, was also noted, as well as whether uprooted or snapped off trees had resprouted, and whether the tree was currently alive or dead.

Uprooted trees were on the ground or in a pile with other trees, with exposed root ball. Crushed trees were smashed to the ground by neighboring trees while their roots remained in the soil. Snapped off trees lost everything above where the trunk broke. Bent trees were defined as those whose trunks were arched as their tops were pushed to the ground by another tree, but which were not uprooted. The trunks of leaning trees remained straight, but at an angle to the ground. Broken trees remained upright but sustained large broken branches. Undamaged trees showed no obvious indication of damage. Although all trees likely lost some branches during the storm, even perhaps large branches, this damage was generally no longer obvious two growing seasons after the storm. Trees that only sustained such no longer detectable damage were classified as undamaged for this study. "Lost" trees were defined as those that were uprooted, crushed, snapped off and died, or were bent far enough that they remained below breast high.

Data analyses

To allow for easier comparison with other studies, which frequently use 10cm dbh as a minimum size (Putz *et al.* 1983, Gresham *et al.* 1991), trees smaller than 10 cm dbh were analyzed separately from larger trees unless otherwise noted. Density and basal area of both standing and lost trees was calculated for each species, and added together to reconstruct pre-hurricane density and basal area for each species at each site (microburst and reference). Pre-hurricane and post-hurricane relative density and relative basal area also were calculated. Importance values (IV) were calculated for each site. Importance value is defined as the average between the relative basal area and relative density of each species. This value is often used in vegetation studies (Dale *et al.* 2007) as a way to summarize overall contribution of a species in a single number.

Total damage for each site was determined by comparing pre-hurricane and post-hurricane basal area of all trees. The total amount of damage was also calculated for each species in each site, as well as the types of damage for each species. Amount and type of damage was also determined for each size class of each species.

Differences between species in frequencies of damage and loss in both reference and microburst areas, as well as differences between the two areas, were tested for significance using Fisher's Exact Test, performed through an online statistical site (http://www.langsrud.com/fisher.htm, accessed Nov. 29-30, 2011). Correlations analyses were carried out between size class and frequency of damage, between size class and frequency of stem loss, and between size class and damage category for both sites using Microsoft Excel.

Results

Composition reconstruction of the original forest

Following Hurricane Isabel, the College Woods were not salvage logged. This made it possible to identify and measure dbh (or what would have been breast high if the trees were still standing) for all trees, standing and lost. By including the number of stems and basal area of the lost trees in the total number of stems and basal area, it was possible to reconstruct the composition of both the reference area and microburst area. A total of 1106 lost and standing trees larger than 5 cm dbh were recorded, with 535 in the reference area and 571 in the microburst. The total number of trees ≥ 10 cm dbh in the reference and microburst areas was 280 and 292, respectively.

Trees greater than 10 cm diameter breast high

Tables 1 through 3 show reconstructed compositions for the reference and microburst areas. Table 1 presents the reconstructed stem number and basal area composition for stems ≥10 cm dbh of the pre-hurricane forest in the reference area, and Table 2 presents the same data for the pre-hurricane forest in the microburst area. Table 3 summarizes the overall pre-hurricane community composition for each of the two areas.

Table 1. Reconstructed pre-hurricane stem number (≥10 cm dbh) and basal area for each species in the reference area.

Tree species	# stems standing	# stems lost	Total # stems	BA standing	BA lost	Total BA
Quercus rubra	7	3	10	21181.85	7356.24	28538.09
Liriodendron tulipifera	29	2	31	70863.52	4070.23	74933.75
Quercus alba	26	0	26	68825.66	0.00	68825.66
Fagus grandifolia	72	2	74	54159.11	1840.04	55999.15
Quercus falcata	5	1	6	18039.10	3017.54	21056.64
Acer rubrum	32	1	33	7459.66	572.27	8031.92
Oxydendron arboreum	16	1	17	4290.81	103.82	4394.63
Ilex opaca	60	0	60	7798.58	0	7798.58
Cornus florida	2	0	2	198.80	0	198.80
Nyssa sylvatica	4	0	4	686.48	0	686.48
Liquidambar styraciflua	0	0	0	0	0	0
Carya tomentosa	2	0	2	266.90	0	266.90
Carya glabra var. *glabra*	0	0	0	0	0	0
Carya pallida	6	0	6	1593.94	0	1593.94
Pinus virginiana	0	0	0	0	0	0
Carpinus caroliniana	0	0	0	0	0	0
Carya glabra var. *ovalis*	3	0	3	1115.49	0	1115.49
Pinus taeda	4	0	4	8765.90	0	8765.90
Quercus velutina	2	0	2	6665.04	0	6665.04
All species combined	270	10	280	271910.85	16960.12	288870.97
Stems/ha	375	13.89	388.89			

Table 2. Reconstructed pre-hurricane stem number (≥10 cm dbh) and basal area for each species in the microburst area.

Tree species	# stems standing	# stems lost	Total # stems	BA standing	BA lost	Total BA
Quercus rubra	1	22	23	2732.59	67140.07	69872.65
Liriodendron tulipifera	13	18	31	10273.49	47196.95	57470.44
Quercus alba	8	13	21	13585.80	40874.95	54460.75
Fagus grandifolia	35	8	43	23282.32	3196.13	26478.44
Quercus falcata	5	3	8	15267.66	7079.52	22347.18
Acer rubrum	15	3	18	5195.52	1651.64	6847.16
Oxydendron arboreum	25	20	45	8542.76	3635.92	12178.69
Ilex opaca	65	8	73	8977.06	1382.58	10359.65
Cornus florida	6	2	8	546.56	165.05	711.60
Nyssa sylvatica	6	1	7	737.51	283.39	1020.89
Liquidambar styraciflua	6	0	6	2208.60	0	2208.60
Carya tomentosa	3	0	3	658.03	0	658.03
Carya glabra var. *glabra*	2	0	2	308.70	0	308.70
Carya pallida	2	0	2	1385.53	0	1385.53
Pinus virginiana	0	1	1	0	1384.74	1384.74
Carpinus caroliniana	1	0	1	86.55	0	86.55
Carya glabra var. *ovalis*	0	0	0	0	0	0
Pinus taeda	0	0	0	0	0	0
Quercus velutina	0	0	0	0	0	0
All species combined	193	99	292	93788.66	173990.93	267779.59
Stems/ha	268.06	137.50	405.56			

Table 3. Community composition pre-hurricane for trees ≥10 cm dbh, ranked by relative basal area in the microburst area.

	Reference					Microburst				
Tree species	Total #	Rel Dens	Total BA	Rel BA	IV	Total #	Rel Dens	Total BA	Rel BA	IV
Quercus rubra	10	3.57	28538.09	9.88	6.73	23	7.88	69872.65	26.09	16.99
Liriodendron tulipifera	31	11.07	74933.75	25.94	18.51	31	10.62	57470.44	21.46	16.04
Quercus alba	26	9.29	68825.66	23.83	16.56	21	7.19	54460.75	20.34	13.76
Fagus grandifolia	74	26.43	55999.15	19.39	22.91	43	14.73	26478.44	9.89	12.31
Quercus falcata	6	2.14	21056.64	7.29	4.72	8	2.74	22347.18	8.35	5.54
Acer rubrum	33	11.79	8031.92	2.78	7.28	18	6.16	6847.16	2.56	4.36
Oxydendron arboreum	17	6.07	4394.63	1.52	3.80	45	15.41	12178.69	4.55	9.98
Ilex opaca	60	21.43	7798.58	2.70	12.06	73	25.00	10359.65	3.87	14.43
Cornus florida	2	0.71	198.80	0.07	0.39	8	2.74	711.60	0.27	1.50
Nyssa sylvatica	4	1.43	686.48	0.24	0.83	7	2.40	1020.89	0.38	1.39
Liquidambar styraciflua	0	0	0	0	0	6	2.05	2208.60	0.82	1.44
Carya tomentosa	2	0.71	266.90	0.09	0.40	3	1.03	658.03	0.25	0.64
Carya glabra var. *glabra*	0	0	0	0	0	2	0.68	308.70	0.12	0.40
Carya pallida	6	2.14	1593.94	0.55	1.35	2	0.68	1385.53	0.52	0.60
Pinus virginiana	0	0	0	0	0	1	0.34	1384.74	0.52	0.43
Carpinus caroliniana	0	0	0	0	0	1	0.34	86.55	0.03	0.19
Carya glabra var. *ovalis*	3	1.07	1115.49	0.39	0.73	0	0	0	0	0
Pinus taeda	4	1.43	8765.90	3.03	2.23	0	0	0	0	0
Quercus velutina	2	0.71	6665.04	2.31	1.51	0	0	0	0	0
All species combined	280	100	288870.97	100	100	292	100	267779.59	100	100
Stems/ha	388.89					405.56				

Prior to the hurricane, the species with the highest relative basal area in the reference was *Liriodendron tulipifera*, followed by *Quercus alba* and *Fagus grandifolia*. *Quercus rubra* came in fourth for relative basal area in the reference area (Table 3). *Fagus grandifolia* had the highest relative density, with *Ilex opaca* and *Acer rubrum* coming in second and third, respectively. *Fagus grandifolia* also had the highest I.V., followed by *L. tulipifera* and *Q. alba.*

In the microburst area, the species with the highest relative basal area was *Quercus rubra,* which ranked fourth in the reference area. *Liriodendron tulipifera* and *Q. alba* had the next highest relative basal areas in the microburst area. Together, these three species comprise 67.89% of the total basal area in the microburst. *Ilex opaca* had the highest relative density in this area, followed by *Oxydendron arboreum* and *Fagus grandifolia.* In contrast, *O. arboreum* ranked 6th for relative density in the reference area. *Quercus rubra* had the highest I.V. for the microburst area, with *L. tulipifera* and *I. opaca* ranked second and third, respectively. *Fagus grandifolia*, which had the highest I.V. in the reference area, ranked fourth for I.V. in the microburst area.

Trees less than 10 cm diameter breast high

Table 4 presents the reconstructed stem number and basal area composition for stems greater than or equal to 5 cm but less than 10 cm dbh (≥ 5 cm, <10 cm dbh) of the pre-hurricane forest in the reference area, and Table 5 presents the same data for the pre-hurricane forest in the microburst area. Table 6 summarizes the overall pre-hurricane community composition for this size class for each of the two areas.

Table 4. Reconstructed pre-hurricane stem number and basal area for small stems (≥ 5 cm, <10 cm dbh) in the reference area.

Tree species	# stems standing	# stems lost	Total # stems	BA standing	BA lost	Total BA
Ilex opaca	119	2	121	4979.65	115.00	5094.65
Cornus florida	23	1	24	966.92	56.72	1023.64
Fagus grandifolia	39	0	39	1874.97	0	1874.97
Acer rubrum	34	1	35	1378.85	63.59	1442.44
Oxydendron arboreum	7	0	7	289.67	0	289.67
Liquidambar styraciflua	2	0	2	89.88	0	89.88
Nyssa sylvatica	9	0	9	331.47	0	331.47
Carpinus caroliniana	2	0	2	94.40	0	94.40
Liriodendron tulipifera	0	0	0	0	0	0
Carya glabra vars. *glabra + ovalis*	4	0	4	231.58	0	231.58
Carya tomentosa	5	0	5	200.96	0	200.96
Juniperus virginiana	0	0	0	0	0	0
Fraxinus pennsylvanica	0	0	0	0	0	0
Carya cordiformis	0	0	0	0	0	0
Quercus rubra	0	0	0	0	0	0
Carya pallida	6	0	6	209.40	0	209.40
Quercus velutina	1	0	1	44.16	0	44.16
All species combined	251	4	255	10691.90	235.30	10927.20
Stems/ha	348.61	5.56	354.17			

Table 5. Reconstructed pre-hurricane stem number and basal area for small stems (≥5 cm, <10 cm dbh) in the microburst area.

Tree species	# stems standing	# stems lost	Total # stems	BA standing	BA lost	Total BA
Ilex opaca	92	9	101	3388.45	311.65	3700.10
Cornus florida	33	12	45	803.64	474.34	1277.98
Fagus grandifolia	35	3	38	1102.14	71.63	1173.77
Acer rubrum	28	2	30	1101.16	52.79	1153.95
Oxydendron arboreum	23	3	26	809.73	158.77	968.49
Liquidambar styraciflua	11	0	11	355.21	0	355.21
Nyssa sylvatica	7	1	8	313.02	19.63	332.64
Carpinus caroliniana	5	1	6	191.54	19.63	211.17
Liriodendron tulipifera	3	0	3	106.76	0	106.76
Carya glabra vars. *glabra* + *ovalis*	3	0	3	85.17	0	85.17
Carya tomentosa	2	0	2	73.99	0	73.99
Juniperus virginiana	2	0	2	61.43	0	61.43
Fraxinus pennsylvanica	1	0	1	50.24	0	50.24
Carya cordiformis	1	1	2	15.90	28.26	44.16
Quercus rubra	1	0	1	19.63	0	19.63
Carya pallida	0	0	0	0	0	0
Quercus velutina	0	0	0	0	0	0
All species combined	247	32	279	8478.00	1136.68	9614.68
Stems/ha	343.06	44.44	387.50			

Table 6. Species composition pre-hurricane for small trees (≥5cm, <10 cm dbh) for both reference and microburst areas, ranked by relative basal area in the microburst area.

	Reference				Microburst			
Tree species	Total # stems	Rel Dens	Total BA	Rel BA	Total # stems	Rel Dens	Total BA	Rel BA
Ilex opaca	121	47.45	5094.65	46.62	101	36.20	3700.10	38.48
Cornus florida	24	9.41	1023.64	9.37	45	16.13	1277.98	13.29
Fagus grandifolia	39	15.29	1874.97	17.16	38	13.62	1173.77	12.21
Acer rubrum	35	13.73	1442.44	13.20	30	10.75	1153.95	12.00
Oxydendron arboreum	7	2.75	289.67	2.65	26	9.32	968.49	10.07
Liquidambar styraciflua	2	0.78	89.88	0.82	11	3.94	355.21	3.69
Nyssa sylvatica	9	3.53	331.47	3.03	8	2.87	332.64	3.46
Carpinus caroliniana	2	0.78	94.40	0.86	6	2.15	211.17	2.20
Liriodendron tulipifera	0	0	0	0	3	1.08	106.76	1.11
Carya glabra vars. *glabra + ovalis*	4	1.57	231.58	2.12	3	1.08	85.17	0.89
Carya tomentosa	5	1.96	200.96	1.84	2	0.72	73.99	0.77
Juniperus virginiana	0	0	0	0	2	0.72	61.43	0.64
Fraxinus pennsylvanica	0	0	0	0	1	0.36	50.24	0.52
Carya cordiformis	0	0	0	0	2	0.72	44.16	0.46
Quercus rubra	0	0	0	0	1	0.36	19.63	0.20
Carya pallida	6	2.35	209.40	1.92	0	0	0	0
Quercus velutina	1	0.39	44.16	0.40	0	0	0	0
All species combined	255	100	10927.20	100	279	100	9614.68	100
Stems/ha	354.17				387.50			

Small stems accounted for 255 of the total 535 individual trees in the reference area. *Ilex opaca* had the highest relative basal area, with 46.62%, followed by *Fagus grandifolia* and *Acer rubrum* (Table 6). *Ilex opaca, F. grandifolia,* and *A. rubrum* also had the highest relative densities. These species, along with *Cornus florida*, were the only species with more than 10 individuals.

The small stems in the microburst area accounted for 279 of the total 571 trees. These smaller trees were primarily *I. opaca,* which had the highest relative basal area and relative density (38.38% and 36.20% respectively), similar to the reference area. *Cornus florida, F. grandifolia*, and *A. rubrum* had the second, third, and fourth highest relative basal areas and relative densities, respectively. In addition to these, *Oxydendron arboreum* and *Liquidambar styraciflua* were the only other species that had over 10 individuals.

Assessment of Damage

Trees greater than 10 cm diameter at breast high

Table 7 shows damage, stem loss, and basal area loss for trees ≥10 cm dbh in the reference area. The total basal area lost in the reference area for trees ≥10 cm dbh was 5.8%. Table 8 shows damage, stem loss, and basal area loss for trees ≥10 cm dbh in the microburst area. The total basal area lost in the microburst area for trees ≥10 cm dbh was 65%. Table 9 shows the community composition post-hurricane for trees ≥10 cm dbh in both the reference and microburst sites.

As shown in Table 7, for those species with more than 10 stems, *Quercus rubra* showed significantly more damage than expected in the reference area, based on the frequency of damage for all species combined (Fisher's Exact Test, hereafter F.E.T, $p = 0.027$). *Fagus grandifolia* and *Ilex opaca* were the least damaged, with 4.05% and 5% damage, respectively. *Quercus rubra* lost significantly more stems than expected based on the frequency of stem loss for all species combined (F.E.T., $p = 0.0035$), while both *Q. alba* and *I. opaca* lost no stems.

The species with the highest basal area loss in the reference area was *Quercus rubra*, with 25.78% basal area loss (Table 7). *Quercus falcata* and *Acer rubrum* followed, losing 14.33% and 7.12% of their basal area, respectively. Similar to stem loss, *Q. alba* and *Ilex opaca* were the only two species that lost no basal area. The only change in basal area rank from pre- to post-hurricane was *I. opaca* moving slightly ahead of *A. rubrum* due to the fact that *I. opaca* lost no basal area.

In the microburst area, *Quercus rubra* suffered the most damage, stem loss, and basal area loss for species with more than 10 individuals, as shown in Table 8. *Quercus rubra* showed more damage than expected (F.E.T., $p < 0.001$) and lost significantly more individuals $\geq$10 cm dbh than expected (F.E.T., $p < 0.001$) based on the frequencies of damage and loss for all species combined. *Quercus rubra* also lost 96.09% of its total basal area. *Quercus alba* and *Liriodendron tulipifera* had the second and third highest damage and individual stem loss for species with more than 10 individuals. *Quercus alba* showed more damage than expected (F.E.T., $p = 0.043$) and more stem loss than expected (F.E.T, $p = 0.0076$) based on the frequencies of damage and loss for all species combined. Similarly, *L. tulipifera* showed more damage (F.E.T., $p = 0.014$) and lost more individuals (F.E.T., $p = 0.0044$) than expected. *Liriodendron tulipifera* and *Q. alba* also had the second and third highest basal area loss, with 82.12% and 75.05% lost, respectively. *Oxydendron arboreum* also showed significantly more damage than expected (F.E.T., $p = 0.015$) and more loss than expected (F.E.T., $p = 0.026$) based on the frequencies of damage and loss for all species combined.

Other species incurred less damage and loss than expected in the microburst area. *Ilex opaca* showed significantly less damage than expected at (F.E.T., $p< 0.001$) and lost significantly fewer individuals ≥10 cm dbh than expected at (F.E.T., $p < 0.001$), based on the frequencies of damage and loss for all species combined. *Fagus grandifolia* also lost significantly fewer individuals than expected (F.E.T., $p = 0.023$). In addition, *I. opaca* and *F. grandifolia* lost the least basal area at 13.35% and 12.07%, respectively.

The basal area rank for several species also changed in the microburst area. The two species with the largest basal area fell in rank, *Quercus rubra* from first to eighth and *Liriodendron tulipifera* from second to fourth. *Fagus grandifolia*, which began in fourth place prior to the hurricane, rose to first.

As shown in Table 9, the three highest relative basal areas in the post-hurricane reference area belonged to *L. tulipifera, Quercus alba*, and *F. grandifolia*, which is the same as the pre-hurricane composition. Also similar to the pre-hurricane

Table 7. Trees ≥10 cm dbh damage, stem loss, basal area loss, and basal area rank before and after the hurricane for each species in the reference area. Fisher's Exact Test was performed on frequency of damage and stem loss for all species with at least 10 stems, and significance ($p < 0.05$) is indicated by an asterisk (*) for values higher than expected based on the frequencies of damage and loss for all species combined.

Tree species	# trees pre-hurricane	# trees damaged	% damaged	# trees lost	% lost	BA pre-hurricane	BA lost	% BA lost	BA rank before	BA rank after
Quercus rubra	10	3	30.00*	3	30.00*	28538.09	7356.24	25.78	4	4
Liriodendron tulipifera	31	3	9.68	2	6.45	74933.75	4070.23	5.43	1	1
Quercus alba	26	2	7.69	0	0	68825.66	0	0	2	2
Fagus grandifolia	74	3	4.05	2	2.70	55999.15	1840.04	3.29	3	3
Quercus falcata	6	1	16.67	1	16.67	21056.64	3017.54	14.33	5	5
Acer rubrum	33	2	6.06	1	3.03	8031.92	572.27	7.12	7	8
Oxydendron arboreum	17	3	17.65	1	5.88	4394.63	103.82	2.36	10	10
Ilex opaca	60	3	5.00	0	0	7798.58	0	0	8	7
Cornus florida	2	0	0	0	0	198.80	0	0	15	15
Nyssa sylvatica	4	0	0	0	0	686.48	0	0	13	13
Liquidambar styraciflua	0	0	0	0	0	0	0	0		
Carya tomentosa	2	0	0	0	0	266.90	0	0	14	14
Carya glabra var. *glabra*	0	0	0	0	0	0	0	0		
Carya pallida	6	0	0	0	0	1593.94	0	0	11	11
Pinus virginiana	0	0	0	0	0	0	0	0		
Carpinus caroliniana	0	0	0	0	0	0	0	0		
Carya glabra var. *ovalis*	3	0	0	0	0	1115.49	0	0	12	12
Pinus taeda	4	0	0	0	0	8765.90	0	0	6	6
Quercus velutina	2	0	0	0	0	6665.04	0	0	9	9
All species combined	280	20	7.14	10	3.57	288870.97	16960.12	5.87		

Table 8. Trees ≥10 cm dbh damage, stem loss, basal area loss, and basal area rank before and after the hurricane for each species in the microburst area. Fisher's Exact Test was performed on frequency of damage and stem loss for all species with at least 10 stems, and significance ($p < 0.05$) is indicated by an asterisk (*) for values higher than expected and a dagger (†) for values lower than expected based on the frequencies of damage and loss for all species combined.

Tree species	# trees pre-hurricane	# trees damaged	% damaged	# trees lost	% lost	BA pre-hurricane	BA lost	% BA lost	BA rank before	BA rank after
Quercus rubra	23	22	95.65*	22	95.65*	69872.65	67140.07	96.09	1	8
Liriodendron tulipifera	31	22	70.97*	18	58.06*	57470.44	47196.95	82.12	2	4
Quercus alba	21	15	71.43*	13	61.90*	54460.75	40874.95	75.05	3	3
Fagus grandifolia	43	16	37.21	8	18.60†	26478.44	3196.13	12.07	4	1
Quercus falcata	8	5	62.50	3	37.50	22347.18	7079.52	31.68	5	2
Acer rubrum	18	8	44.44	3	16.67	6847.16	1651.64	24.12	8	7
Oxydendron arboreum	45	30	66.67*	20	44.44*	12178.69	3635.92	29.85	6	6
Ilex opaca	73	15	20.55†	8	10.96†	10359.65	1382.58	13.35	7	5
Cornus florida	8	6	75.00	2	25.00	711.60	165.05	23.19	13	13
Nyssa sylvatica	7	3	42.86	1	14.29	1020.89	283.39	27.76	12	11
Liquidambar styraciflua	6	1	16.67	0	0	2208.60	0	0	9	9
Carya tomentosa	3	1	33.33	0	0	658.03	0	0	14	12
Carya glabra var. *glabra*	2	0	0	0	0	308.70	0	0	15	14
Carya pallida	2	0	0	0	0	1385.53	0	0	10	10
Pinus virginiana	1	1	100	1	100	1384.74	1384.74	100	11	16
Carpinus caroliniana	1	0	0	0	0	86.55	0	0	16	15
Carya glabra var. *ovalis*	0	0	0	0	0	0	0	0		
Pinus taeda	0	0	0	0	0	0	0	0		
Quercus velutina	0	0	0	0	0	0	0	0		
All species combined	292	145	49.66	99	33.90	267779.59	173990.93	64.98		

Table 9. Community composition post-hurricane for trees ≥10 cm dbh, ranked by relative basal area in the microburst area.

	Reference					Microburst				
Tree species	Total #	Rel dens	Total BA	Rel BA	IV	Total #	Rel dens	Total BA	Rel BA	IV
Fagus grandifolia	72	26.67	54159.11	19.92	23.29	35	18.13	23282.32	24.82	21.48
Quercus falcata	5	1.85	18039.10	6.63	4.24	5	2.59	15267.66	16.28	9.43
Quercus alba	26	9.63	68825.66	25.31	17.47	8	4.15	13585.80	14.49	9.32
Liriodendron tulipifera	29	10.74	70863.52	26.06	18.40	13	6.74	10273.49	10.95	8.84
Ilex opaca	60	22.22	7798.58	2.87	12.55	65	33.68	8977.06	9.57	21.63
Oxydendron arboreum	16	5.93	4290.81	1.58	3.75	25	12.95	8542.76	9.11	11.03
Acer rubrum	32	11.85	7459.66	2.74	7.30	15	7.77	5195.52	5.54	6.66
Quercus rubra	7	2.59	21181.85	7.79	5.19	1	0.52	2732.59	2.91	1.72
Liquidambar styraciflua	0	0	0	0	0	6	3.11	2208.60	2.35	2.73
Carya pallida	6	2.22	1593.94	0.59	1.40	2	1.04	1385.53	1.48	1.26
Nyssa sylvatica	4	1.48	686.48	0.25	0.87	6	3.11	737.51	0.79	1.95
Carya tomentosa	2	0.74	266.90	0.10	0.42	3	1.55	658.03	0.70	1.13
Cornus florida	2	0.74	198.80	0.07	0.41	6	3.11	546.56	0.58	1.85
Carya glabra var. *glabra*	0	0	0	0	0	2	1.04	308.70	0.33	0.68
Carpinus caroliniana	0	0	0	0	0	1	0.52	86.55	0.09	0.31
Pinus virginiana	0	0	0	0	0	0	0	0	0	0
Carya glabra var. *ovalis*	3	1.11	1115.49	0.41	0.76	0	0	0	0	0
Pinus taeda	4	1.48	8765.90	3.22	2.35	0	0	0	0	0
Quercus velutina	2	0.74	6665.04	2.45	1.60	0	0	0	0	0
All species combined	270	100	271910.85	100	100	193	100	93788.66	100	100
Stems/ha	375					268				

Table 10. Comparison of damage, stem loss rates, and basal area loss rates for trees ≥10 cm dbh in the reference and microburst areas for species with at least 10 stems. Fisher's Exact Test was performed on frequency of damage and stem loss across sites for each species. Asterisks indicate that frequency of damage or loss for that species in the microburst area is significantly higher than in the reference area (F.E.T, ** = $p < 0.001$; * = $p < 0.05$)

Tree species	Reference % Tree Damage	Microburst % Tree Damage	Reference % Stem Loss	Microburst % Stem Loss	Reference % BA Loss	Microburst % BA Loss
Quercus rubra	30.00	95.65**	30.00	95.65**	25.78	96.09
Liriodendron tulipifera	9.68	70.97**	6.45	58.06**	5.43	82.12
Quercus alba	7.69	71.43**	0	61.90**	0	75.05
Fagus grandifolia	4.05	37.21**	2.70	18.60*	3.29	12.07
Acer rubrum	6.06	44.44*	3.03	16.67	7.12	24.12
Oxydendron arboreum	17.65	66.67**	5.88	44.44**	2.36	29.85
Ilex opaca	5.00	20.55*	0	10.96*	0	13.35
All species combined	7.14	49.66**	3.57	33.90**	5.87	64.98

composition, the species with the first, second, and third highest relative densities were *F. grandifolia*, *Ilex opaca* and *Acer rubrum*, respectively.

The species with the highest relative basal area in the post-hurricane microburst site was *Fagus grandifolia* (Table 9). *Quercus falcata* and *Q. alba* followed with the second and third highest relative basal areas, respectively. *Ilex opaca* had the highest relative density, followed by *F. grandifolia* and *Oxydendron arboreum*.

Table 10 compares percent total damage, percent stem loss, and percent basal area loss for trees ≥10 cm dbh in the reference and microburst areas for all species with at least ten stems.

Most species with at least 10 individuals ≥10 cm dbh in the microburst area were significantly more likely to be damaged and lost significantly more stems than in the reference area. *Acer rubrum* is the only species that did not lose significantly more stems in the microburst area. In addition, the microburst area showed significant damage and stem loss for all species combined.

Trees less than 10 cm at breast high

Smaller trees ≥5cm, <10 cm dbh were also damaged in both areas, usually experiencing secondary damage in·the microburst area through contact with larger trees. Table 11 and Table 12 show small tree damage, stem loss, and basal area loss in the reference and microburst areas, respectively. Table 13 shows the post-hurricane relative densities and basal areas for small trees of each species in both areas.

In the reference area, damage, stem loss, and basal area loss were low overall and for individual species (Table 11). For species with at least 10 individuals, *Acer rubrum* had the highest level of damage, and *Cornus florida* had the most stem and basal area loss. No species showed significantly more or less damage than expected, and no species lost significantly more or fewer individuals than expected, based on the frequencies of damage and loss for all species combined. In addition, no species changed basal area rank from pre- to post-hurricane.

In the microburst area, of the trees that had at least 10 individuals, *Cornus florida* showed the greatest damage, stem loss, and basal area lost for trees ≥5cm, <10 cm dbh (Table 12). In this size class, *C. florida* suffered significantly more damage than

Table 11. Trees ≥5 cm, <10 cm dbh damage, stem loss, basal area loss, and basal area rank before and after the hurricane for each species in the reference area. Fisher's Exact Test was performed on frequency of damage and stem loss for all species with at least 10 stems. No values were significantly higher or lower than expected based on the frequencies of damage and loss for all species combined.

Tree species	# trees pre-hurricane	# trees damaged	% damaged	# trees lost	% lost	BA pre-hurricane	BA lost	% BA lost	BA rank before	BA rank after
Ilex opaca	121	6	4.96	2	1.65	5094.65	115.00	2.26	1	1
Cornus florida	24	1	4.17	1	4.17	1023.64	56.72	5.54	4	4
Fagus grandifolia	39	0	0	0	0	1874.97	0	0	2	2
Acer rubrum	35	4	11.43	1	2.86	1442.44	63.59	4.41	3	3
Oxydendron arboreum	7	1	14.29	0	0	289.67	0	0	6	6
Liquidambar styraciflua	2	0	0	0	0	89.88	0	0	11	11
Nyssa sylvatica	9	0	0	0	0	331.47	0	0	5	5
Carpinus caroliniana	2	0	0	0	0	94.40	0	0	10	10
Liriodendron tulipifera	0	0	0	0	0	0	0	0		
Carya glabra vars. *glabra + ovalis*	4	1	25.00	0	0	231.58	0	0	7	7
Carya tomentosa	5	0	0	0	0	200.96	0	0	9	9
Juniperus virginiana	0	0	0	0	0	0	0	0		
Fraxinus pennsylvanica	0	0	0	0	0	0	0	0		
Carya cordiformis	0	0	0	0	0	0	0	0		
Quercus rubra	0	0	0	0	0	0	0	0		
Carya pallida	6	0	0	0	0	209.40	0	0	8	8
Quercus velutina	1	0	0	0	0	44.16	0	0	12	12
All species combined	255	13	5.10	4	1.57	10927.20	235.30	2.15		

Table 12. Trees ≥5 cm, <10 cm dbh damage, stem loss, basal area loss, and basal area rank before and after the hurricane for each species in the microburst area. Fisher's Exact Test was performed on frequency of damage and stem loss for all species with at least 10 stems, and significance ($p < 0.05$) is indicated by an asterisk (*) for values higher than expected and a dagger (†) for values lower than expected based on the frequencies of damage and loss for all species combined.

Tree species	# trees pre-hurricane	# trees damaged	% damaged	# trees lost	% lost	BA pre-hurricane	BA lost	% BA lost	BA rank before	BA rank before
Ilex opaca	101	23	22.77†	9	8.91	3700.10	311.65	7.77	1	1
Cornus florida	45	21	46.67*	12	26.67*	1277.98	474.34	27.07	2	5
Fagus grandifolia	38	17	44.74	3	7.89	1173.77	71.63	5.75	3	2
Acer rubrum	30	8	26.67	2	6.67	1153.95	52.79	4.37	4	3
Oxydendron arboreum	26	11	42.31	3	11.54	968.49	158.77	14.08	5	4
Liquidambar styraciflua	11	0	0†	0	0	355.21	0	0	6	6
Nyssa sylvatica	8	4	50.00	1	12.50	332.64	19.63	5.57	7	7
Carpinus caroliniana	6	2	33.33	1	16.67	211.17	19.63	8.50	8	8
Liriodendron tulipifera	3	0	0	0	0	106.76	0	0	9	9
Carya glabra vars. *glabra + ovalis*	3	0	0	0	0	85.17	0	0	10	10
Carya tomentosa	2	2	100	0	0	73.99	0	0	11	11
Juniperus virginiana	2	0	0	0	0	61.43	0	0	12	12
Fraxinus pennsylvanica	1	0	0	0	0	50.24	0	0	13	13
Carya cordiformis	2	2	100	1	50.00	44.16	28.26	39.02	14	15
Quercus rubra	1	0	0	0	0	19.63	0	0	15	14
Carya pallida	0	0	0	0	0	0	0	0		
Quercus velutina	0	0	0	0	0	0	0	0		
All species combined	279	90	32.26	32	11.47	9614.68	1136.68	11.82		

Table 13. Community composition post-hurricane for trees ≥5 cm, <10 cm dbh, ranked by relative basal area in the microburst area.

	Reference				Microburst			
Tree species	Total #	Rel dens	Total BA	Rel BA	Total #	Rel dens	Total BA	Rel BA
Ilex opaca	119	47.41	4979.65	46.57	92	37.25	3388.45	39.97
Fagus grandifolia	39	15.54	1874.97	17.54	35	14.17	1102.14	13.00
Acer rubrum	34	13.55	1378.85	12.90	28	11.34	1101.16	12.99
Oxydendron arboreum	7	2.79	289.67	2.71	23	9.31	809.73	9.55
Cornus florida	23	9.16	966.92	9.04	33	13.36	803.64	9.48
Liquidambar styraciflua	2	0.80	89.88	0.84	11	4.45	355.21	4.19
Nyssa sylvatica	9	3.59	331.47	3.10	7	2.83	313.02	3.69
Carpinus caroliniana	2	0.80	94.40	0.88	5	2.02	191.54	2.26
Liriodendron tulipifera	0	0	0.00	0	3	1.21	106.76	1.26
Carya glabra vars. *glabra* + *ovalis*	4	1.59	231.58	2.17	3	1.21	85.17	1.00
Carya tomentosa	5	1.99	200.96	1.88	2	0.81	73.99	0.87
Juniperus virginiana	0	0	0.00	0	2	0.81	61.43	0.72
Fraxinus pennsylvanica	0	0	0.00	0	1	0.40	50.24	0.59
Quercus rubra	0	0	0.00	0	1	0.40	19.63	0.23
Carya cordiformis	0	0	0.00	0	1	0.40	15.90	0.19
Carya pallida	6	2.39	209.40	1.96	0	0	0.00	0
Quercus velutina	1	0.40	44.16	0.41	0	0	0.00	0
All species combined	251	100	10691.90	100	247	100	8478.00	100
Stems/ha	349				343			

Table 14. Comparison of damage, stem loss rates, and basal area loss rates for trees ≥5 cm, <10 cm dbh in the reference and microburst areas with at least 10 stems. Fisher's Exact Test was performed on frequency of damage and stem loss across sites for all species. Asterisks indicate that frequency of damage or loss for that species in the microburst area is significantly higher than in the reference area (F.E.T., ** = $p < 0.001$; * = $p < 0.05$).

Tree species	Reference % Tree Damage	Microburst % Tree Damage	Reference % Stem Loss	Microburst % Stem Loss	Reference % BA Loss	Microburst % BA Loss
Ilex opaca	4.96	22.77**	1.65	8.91	2.26	7.77
Cornus florida	4.17	46.67**	4.17	26.67*	5.54	27.07
Fagus grandifolia	0	44.74**	0	7.89	0	5.75
Acer rubrum	11.43	26.67	2.86	6.67	4.41	4.37
All species combined	5.10	32.26**	1.57	11.47**	2.15	11.82

expected (F.E.T., $p = 0.036$) and significantly more individuals lost (F.E.T., $p = 0.0015$), based on the frequencies of damage and loss for all species combined. In addition, *C. florida* showed 27% basal area loss and also dropped in basal area rank, from second pre-hurricane to fifth post-hurricane.

Ilex opaca experienced significantly less damage than expected to trees ≥5cm, <10 cm dbh in the microburst area (F.E.T., $p = 0.012$), based on the frequency of damage for all species combined. *Liquidambar styraciflua* also showed significantly less damage than expected (F.E.T., $p = 0.019$). No other species showed significantly more or less damage than expected for this size class based on the frequency of damage for all species combined.

Table 14 compares percent total damage, percent stem loss, and percent basal area loss for trees ≥5 cm, <10 cm dbh in the reference and microburst areas for all species with at least ten stems. In the microburst area, *Cornus florida* showed both a greater likelihood of damage as well as stem loss than expected for small trees in the microburst area when compared to the reference area. *Fagus grandifolia* and *Ilex opaca* also showed greater damage in the microburst area. In addition, all small tree species combined showed a greater likelihood of being damaged as well as greater stem loss in the microburst area, similar to trees ≥10 cm dbh.

Damage and stem size

Damage and loss by stem size in the reference area is shown in Table 15, while that for the microburst area is shown in Table 16. The reference area showed no significant correlation between size class and either percent damaged ($r = -0.25$) or percent lost ($r = -0.28$). In contrast, in the microburst area the correlation between size class and percent damage was 0.978 and between size class and percent lost was 0.869, both significant at the $p < 0.01$ level.

Table 15. Damage, stem loss, and basal area loss by size class in the reference area. The correlation coefficients between size and percent damaged ($r = -0.25$) and size and percent stem loss ($r = -0.28$) were not significant.

Size class	# trees	# damaged	% damaged	# lost	% lost	BA lost	% BA lost
≥5--10 cm	255	13	5.10	4	1.57	235.30	2.15
≥10--20 cm	148	7	4.73	1	0.68	103.82	0.46
≥20--30 cm	35	2	5.71	2	5.71	1278.77	7.66
≥30--40 cm	21	1	4.76	1	4.76	1133.54	5.84
≥40--50 cm	18	4	22.22	3	16.67	5138.61	17.61
≥50--60 cm	19	1	5.26	1	5.26	2550.47	5.64
≥60--70 cm	23	4	17.39	2	8.70	6754.93	8.84
≥70--80 cm	11	1	9.09	0	0	0	0
≥80--90 cm	3	0	0	0	0	0	0
≥90--100 cm	1	0	0	0	0	0	0
≥100 cm	1	0	0	0	0	0	0
All sizes combined	535	33	6.17	14	2.62	17195.43	5.74

Table 16. Damage, stem loss, and basal area loss by size class in the microburst area. The correlation coefficient between size and percent damaged was 0.98 and that between size and percent stem loss was 0.87, both statistically significant at $p < 0.01$.

Size class	# trees	# damaged	% damaged	# lost	% lost	BA lost	% BA lost
≥5--10 cm	279	90	32.26	32	11.47	1136.68	10.57
≥10--20 cm	164	60	36.59	34	20.73	5289.53	22.10
≥20--30 cm	37	16	43.24	10	27.03	4568.50	26.13
≥30--40 cm	25	14	56.00	6	24.00	5327.21	22.95
≥40--50 cm	7	5	71.43	3	42.86	5270.69	45.75
≥50--60 cm	24	17	70.83	15	62.50	36106.08	63.31
≥60--70 cm	20	18	90.00	18	90.00	57785.03	88.98
≥70--80 cm	12	12	100	11	91.67	47630.07	92.43
≥80--90 cm	2	2	100	1	50.00	5473.22	46.81
≥90--100 cm	1	1	100	1	100	6429.35	100
≥100 cm	0	0	0	0	0	0	0
All sizes combined	571	235	41.16	131	22.94	175016.34	62.84

Damage categories and tree size

Stem size affected not only the amount of damage from the storm, but also the kind of damage experienced. Damage classifications according to size can be seen in Tables 17 and 18 for the reference and microburst areas, respectively. In the reference area, there was no significant correlation between size class and percent uprooted ($r = -0.19$) or between size class and percent damaged ($r = -0.17$). In contrast, in the microburst area the correlation between increasing size class and an increase in percent uprooted was 0.662 and the correlation between increasing size class and increased percent damaged was 0.908, both significant at the $p < 0.01$ level.

In both the reference and microburst areas, "bent", "crush", and "lean" categories tended to affect smaller tree sizes (Table 17 and Table 18). In fact, bent

Table 17. Damage categories by size class in the reference area. The correlation coefficient between size and percent damaged (r = -0.17) and size and percent uprooted (r = -0.19) were not significant.

Size class	Total #	% All trees	# Bent	% Bent	# Broken	% Broken	# Snapped off	% Snapped off	# Crush	% Crush	# Lean	% Lean	# Uprooted	% Uprooted	Total # damaged	% Damaged	# Undamaged	% Undamaged
≥5--10 cm	255	47.66	4	1.57	1	0.39	1	0.39	0	0	4	1.57	3	1.18	13	5.10	242	94.90
≥10--15 cm	105	19.63	0	0	1	0.95	0	0	1	0.95	4	3.81	0	0	6	5.71	99	94.29
≥15--20 cm	43	8.04	0	0	0	0	0	0	0	0	1	2.33	0	0	1	2.33	42	97.67
≥20--25 cm	22	4.11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	22	100
≥25--30 cm	13	2.43	0	0	0	0	1	7.69	0	0	0	0	1	7.69	2	15.38	11	84.62
≥30--35 cm	14	2.62	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14	100
≥35--40 cm	7	1.31	0	0	0	0	0	0	0	0	0	0	1	14.29	1	14.29	6	85.71
≥40--45 cm	7	1.31	0	0	0	0	0	0	0	0	0	0	1	14.29	1	14.29	6	85.71
≥45--50 cm	11	2.06	0	0	0	0	1	9.09	0	0	1	9.09	1	9.09	3	27.27	8	72.73
≥50--55 cm	10	1.87	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	100
≥55--60 cm	9	1.68	0	0	0	0	0	0	0	0	0	0	1	11.11	1	11.11	8	88.89
≥60--65 cm	15	2.80	0	0	2	13.33	0	0	0	0	1	6.67	0	0	3	20.00	12	80.00
≥65--70 cm	8	1.50	0	0	0	0	0	0	0	0	0	0	1	12.50	1	12.50	7	87.50
≥70--75 cm	6	1.12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	100
≥75--80 cm	5	0.93	0	0	1	20.00	0	0	0	0	0	0	0	0	1	20.00	4	80.00
≥80--85 cm	2	0.37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	100
≥85--90 cm	1	0.19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	100
≥90--95 cm	1	0.19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	100
≥95--100 cm	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
≥100--105 cm	1	0.19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	100
All sizes combined	535	100	4	0.75	5	0.93	3	0.56	1	0.19	11	2.06	9	1.68	33	6.17	502	93.83

Table 18. Damage categories by size class in the microburst area. The correlation coefficient between size and percent damaged was 0.91 and between size and percent uprooted was 0.66, both statistically significant at $p < 0.01$.

Size class	Total #	% All trees	# Bent	% Bent	# Broken	% Broken	# Snapped off	% Snapped off	# Crush	% Crush	# Lean	% Lean	# Uprooted	% Uprooted	Total # damaged	% Damaged	# Undamaged	% Undamaged
≥5--10 cm	279	48.86	45	16.13	1	0.36	18	6.45	10	3.58	9	3.23	7	2.51	90	32.26	189	67.74
≥10--15 cm	124	21.72	10	8.06	2	1.61	6	4.84	8	6.45	8	6.45	12	9.68	46	37.10	78	62.90
≥15--20 cm	40	7.01	3	7.50	0	0	2	5	2	5	0	0	7	17.5	14	35.00	26	65.00
≥20--25 cm	21	3.68	1	4.76	0	0	0	0	0	0	1	4.76	7	33.33	9	42.86	12	57.14
≥25--30 cm	16	2.80	0	0	0	0	1	6.25	0	0	3	18.75	3	18.75	7	43.75	9	56.25
≥30--35 cm	14	2.45	0	0	1	7.14	6	42.86	0	0	0	0	2	14.29	9	64.29	5	35.71
≥35--40 cm	11	1.93	0	0	1	9.09	2	18.18	0	0	0	0	2	18.18	5	45.45	6	54.55
≥40--45 cm	4	0.70	0	0	0	0	1	25	0	0	1	25.00	0	0	2	50.00	2	50.00
≥45--50 cm	3	0.53	0	0	1	33.33	0	0	0	0	0	0	2	66.67	3	100	0	0
≥50--55 cm	13	2.28	0	0	0	0	2	15.38	0	0	0	0	7	53.85	9	69.23	4	30.77
≥55--60 cm	11	1.93	0	0	0	0	0	0	0	0	0	0	8	72.73	8	72.73	3	27.27
≥60--65 cm	13	2.28	0	0	0	0	2	15.38	0	0	0	0	10	76.92	12	92.31	1	7.69
≥65--70 cm	7	1.23	0	0	0	0	2	28.57	0	0	0	0	3	42.86	5	71.43	2	28.57
≥70--75 cm	8	1.40	0	0	0	0	4	50	0	0	0	0	4	50.00	8	100	0	0
≥75--80 cm	4	0.70	0	0	0	0	0	0	0	0	0	0	4	100	4	100	0	0
≥80--85 cm	1	0.18	0	0	0	0	0	0	0	0	0	0	1	100	1	100	0	0
≥85--90 cm	1	0.18	0	0	0	0	1	100	0	0	0	0	0	0	1	100	0	0
≥90--95 cm	1	0.18	0	0	0	0	0	0	0	0	0	0	1	100	1	100	0	0
All sizes combined	571	100	59	10.33	6	1.05	47	8.23	20	3.50	22	3.85	80	14.01	234	40.98	337	59.02

and crush categories only applied to trees smaller than 25 cm dbh in both areas. These categories describe secondary damage generally inflicted by falling neighboring trees, which has a greater potential to affect smaller trees. "Uprooted" smaller trees were also due to secondary damage, often when a nearby larger tree fell and took the small tree along with it. Trees less than 30 cm dbh were almost never tall enough to catch much wind, since taller trees around served as windbreaks (Prengaman *et al.* 2008).

In the microburst area, 34.58% of trees <30 cm dbh were damaged, while 74.73% of trees ≥30 cm dbh were damaged. In these larger trees, "snapped off" and "uprooted" damage categories were more prevalent. In fact, all damaged individuals ≥50 cm dbh in the microburst area were either snapped off or uprooted.

Damage categories and species

Table 19 presents damage categories for individuals ≥10 cm dbh of each species in the reference area, and Table 20 presents the same data for the microburst area. In both the reference and microburst areas, species that tend to have smaller stems experienced more secondary damage. *Oxydendron arboreum*, for example, was the species with more than 10 individuals most likely to be bent or crushed in both areas. Those species that tend to be larger were affected more by uprooting and breaking, such as *Quercus rubra* in the reference area and *Q. rubra* and *Q. alba* in the microburst area. *Quercus rubra* had significantly more individuals uprooted than expected in the reference area (F.E.T., $p = 0.016$), based on the frequency of uprooting for all species combined. *Quercus rubra* also showed a significantly lower

Table 19. Damage categories by tree species for individuals ≥10 cm dbh in the reference area. Fisher's Exact Test was performed on frequency of uprooting and undamaged for all species with at least 10 stems, and significance ($p < 0.05$) is indicated by an asterisk (*) for values higher than expected and a dagger (†) for values lower than expected based on the frequencies of damage and loss for all species combined.

Tree species	Total #	% All trees	# Bent	% Bent	# Broken	% Broken	# Snapped off	% Snapped off	# Crush	% Crush	# Lean	% Lean	# Uprooted	% Uprooted	# Undamaged	% Undamaged
Quercus rubra	10	3.57	0	0	0	0	1	10	0	0	0	0	2	20.00*	7	70.00†
Liriodendron tulipifera	31	11.07	0	0	0	0	0	0	0	0	1	3.23	2	6.45	28	90.32
Quercus alba	26	9.29	0	0	1	3.85	0	0	0	0	1	3.85	0	0	24	92.31
Fagus grandifolia	74	26.43	0	0	1	1.35	1	1.35	0	0	0	0	1	1.35	71	95.95
Quercus falcata	6	2.14	0	0	1	16.67	0	0	0	0	0	0	0	0	5	83.33
Acer rubrum	33	11.79	0	0	0	0	0	0	0	0	1	3.03	1	3.03	31	93.94
Oxydendron arboreum	17	6.07	0	0	0	0	0	0	1	5.88	2	11.76	0	0	14	82.35
Ilex opaca	60	21.43	0	0	1	1.67	0	0	0	0	2	3.33	0	0	57	95.00
Cornus florida	2	0.71	0	0	0	0	0	0	0	0	0	0	0	0	2	100
Nyssa sylvatica	4	1.43	0	0	0	0	0	0	0	0	0	0	0	0	4	100
Carya tomentosa	2	0.71	0	0	0	0	0	0	0	0	0	0	0	0	2	100
Carya glabra var. *ovalis*	3	1.07	0	0	0	0	0	0	0	0	0	0	0	0	3	100
Carya pallida	6	2.14	0	0	0	0	0	0	0	0	0	0	0	0	6	100
Pinus taeda	4	1.43	0	0	0	0	0	0	0	0	0	0	0	0	4	100
Quercus velutina	2	0.71	0	0	0	0	0	0	0	0	0	0	0	0	2	100
All species combined	280	100	0	0	4	1.43	2	0.71	1	0.36	7	2.50	6	2.14	260	92.86

Table 20. Damage categories by tree species for individuals ≥10 cm dbh in the microburst area. Fisher's Exact Test was performed on frequency of uprooting and undamaged for all species with at least 10 stems, and significance ($p < 0.05$) is indicated by an asterisk (*) for values higher than expected and a dagger (†) for values lower than expected based on the frequencies of damage and loss for all species combined.

Tree species	Total #	% All trees	# Bent	% Bent	# Broken	% Broken	# Snapped off	% Snapped off	# Crush	% Crush	# Lean	% Lean	# Uprooted	% Uprooted	# Undamaged	% Undamaged
Quercus rubra	23	7.88	0	0	0	0	4	17.39	0	0	0	0	17	73.91*	2	8.70†
Liriodendron tulipifera	31	10.62	1	3.23	0	0	2	6.45	0	0	2	6.45	17	54.84*	9	29.03†
Quercus alba	21	7.19	0	0	0	0	5	23.81	0	0	0	0	10	47.62*	6	28.57†
Fagus grandifolia	43	14.73	1	2.33	2	4.65	7	16.28	1	2.33	0	0	5	11.63†	27	62.79
Quercus falcata	8	2.74	0	0	0	0	3	37.50	0	0	0	0	2	25.00	3	37.50
Acer rubrum	18	6.16	1	5.56	1	5.56	1	5.56	0	0	2	11.11	3	16.67	10	55.56
Oxydendron arboreum	45	15.41	4	8.89	1	2.22	3	6.67	6	13.33	3	6.67	13	28.89	15	33.33†
Ilex opaca	73	25.00	2	2.74	1	1.37	1	1.37	1	1.37	5	6.85	5	6.85†	58	79.45*
Cornus florida	8	2.74	2	25.00	0	0	1	12.50	1	12.50	1	12.50	1	12.50	2	25.00
Nyssa sylvatica	7	2.40	0	0	0	0	2	28.57	1	14.29	0	0	0	0	4	57.14
Liquidambar styraciflua	6	2.05	1	16.67	0	0	0	0	0	0	0	0	0	0	5	83.33
Carya tomentosa	3	1.03	1	33.33	0	0	0	0	0	0	0	0	0	0	2	66.67
Carya glabra var. *glabra*	2	0.68	0	0	0	0	0	0	0	0	0	0	0	0	2	100
Carya pallida	2	0.68	0	0	0	0	0	0	0	0	0	0	0	0	2	100
Pinus virginiana	1	0.34	0	0	0	0	1	100	0	0	0	0	0	0	0	0
Carpinus caroliniana	1	0.34	0	0	0	0	0	0	0	0	0	0	0	0	1	100
All species combined	292	100	13	4.45	5	1.71	30	10.27	10	3.42	13	4.45	73	25	148	50.68

frequency of undamaged individuals than expected (F.E.T., $p = 0.027$) based on the frequency for undamaged individuals for all species combined.

Quercus rubra had significantly more individuals uprooted than expected in the microburst area (F.E.T., $p < 0.001$), as did *Liriodendron tulipifera* (F.E.T., $p < 0.001$) and *Q. alba* (F.E.T., $p = 0.019$), based on the frequency of uprooting for all species combined. In contrast, *Fagus grandifolia* had significantly fewer trees uprooted than expected in the microburst area (F.E.T., $p = 0.035$), as did *Ilex opaca* (F.E.T., $p < 0.01$), based on the frequency of uprooting for all species combined.

Several species showed significantly lower frequencies of undamaged individuals than expected, based on the frequency for undamaged individuals for all species combined. These species were *Quercus rubra* (F.E.T., $p < 0.001$), *Liriodendron tulipifera* (F.E.T., $p = 0.013$), *Q. alba* (F.E.T., $p = 0.042$), and *Oxydendron arboreum* (F.E.T., $p = 0.015$). *Ilex opaca* showed a significantly higher frequency of undamaged individuals (F.E.T., $p <0.001$).

Sprouting of lost trees

Although uprooted, crushed, and many snapped off trees are considered lost, sometimes these trees do not actually die, but survive and even send up new sprouts that can contribute to the future composition of the forest. Several damaged trees showed signs of sprouting during the field season of this study, 3 years after Hurricane Isabel hit in 2003. The species and damage classes that sprouted are shown in Table 21. In the microburst area, 16% of lost trees sprouted following the wind disturbance (n=16 of 99 lost trees larger than 10 cm dbh). Of these, all but one tree continued to have living sprouts during the summer of 2005. This indicates that all but one of the trees were still alive during data collection, even though they were considered "lost". However, the sprouts on all the larger uprooted trees were dead by the summer of 2007 (S. Ware, personal communication)

A total of 73 trees larger than 10 cm dbh were uprooted in the microburst, and of these 12 sprouted (16%). Crushed trees showed 30% sprouting (3 of 10). The single snapped off tree classified as lost also sprouted.

Table 21. Tree species, damage category, and size class for sprouting "lost" trees in the microburst area. All but one individual (marked with #) bore living sprouts during the field season when data were collected. A total of 99 trees were lost in this area.

Tree species	Damage	Size Class
Acer rubrum	Uprooted	20
Acer rubrum	Uprooted	30
Cornus florida	Crush	20
Ilex opaca	Uprooted	20
Ilex opaca	Crush	20
Liriodendron tulipifera	Uprooted	30
Liriodendron tulipifera	Uprooted	60
Liriodendron tulipifera	Uprooted	60
Liriodendron tulipifera	Uprooted	60
Liriodendron tulipifera	Uprooted	90
Oxydendron arboreum	Uprooted	20
Oxydendron arboreum	Uprooted	20
Oxydendron arboreum	Uprooted	20
Oxydendron arboreum	Crush	20
Quercus alba#	Uprooted	70
Quercus alba	Snapped off	70

Discussion

Pre-disturbance composition reconstruction

When no sample plots were present before a disturbance, use of an adjacent undisturbed site as a stand-in for pre-disturbance composition of a forest is common (Webb 1989, Orwig and Abrams 1995, Webb and Scanga 2001). However, assuming that pre-disturbance species composition was like a nearby forest may not give the most accurate portrait of the disturbed area. In this study, even though the reference plots were only 40 m from the microburst site, the species composition of the two sites was different. The species with the largest basal area for large trees (≥10 cm dbh) in the reference site were *Liriodendron tulipifera*, *Quercus alba*, and *Fagus grandifolia*, in that order, while the three species with the largest basal area for large trees in the microburst site were *Q. rubra*, *L. tulipifera*, and *Q. alba* (Table 3). The species with the largest basal area for small trees (≥ 5 cm, <10 cm dbh) in the reference site were *Ilex opaca*, *F. grandifolia, Acer rubrum*, *Cornus florida,* and *Nyssa sylvatica*, while the species with the largest basal area for small trees for the microburst site were *I. opaca, C. florida, F. grandifolia, A. rubrum,* and *Oxydendron arboreum* (Table 6).

While *Quercus alba* and *Liriodendron tulipifera* were among the top three species for basal area in each site, reference and microburst sites showed different ranks among the dominant species. There were also some differences in abundances in the small tree size class of the two forest areas. This difference in pre-disturbance species dominance between the reference and microburst sites shows the importance of pre-disturbance reconstruction over use of nearby less disturbed sites for comparison.

Reconstructing pre-disturbance forest composition is possible only when no salvage logging has taken place. However, this reconstruction must take place before fallen trees have begun to rot (for tree identification purposes), as well as before any additional disturbance. It was the lack of salvage logging in this forest preserve that made this study possible.

The abundance rank of species for both small and large trees in the reference and microburst sites was somewhat different than the composition previously reported for the College Woods (Prengaman *et al.* 2008, Kribel *et al.* 2011). However the plots in those previous studies were spread over a larger portion of the College Woods and likely reflect the overall patchiness of the forest, as opposed to a short-coming of reconstruction. This is also likely true for the difference between the reference and microburst sites in this study.

Differences in damage in microburst and reference sites

The results of this study show that the microburst site suffered more total damage and loss than the reference site. The loss of 65% of total basal area in the microburst indicates that this disturbance event, though brief, caused considerable damage. Also, the loss of 5.8% of total basal area in the reference site indicates that even relatively intact areas of the forest still sustained damage from general hurricane winds.

In addition to basal area loss, the microburst site lost 33.9% of total trees (Table 8), while the reference area lost 3.57% (Table 7). While this may seem less severe than the basal area loss, the great loss of individual trees is important for forest structure. Canopy gaps created by a large number of treefalls allow for the growth of new seedlings, while a smaller gap mostly allows the growth of understory trees (Foster *et al.* 1998).

Prengaman *et al.* (2008) found higher percent loss for their sample sites in the College Woods than found in the reference area of this study. Their study showed 27.2% damage and16.3% loss for larger trees (>20 cm dbh), and 11.6% damage for smaller trees (<20 cm dbh). The reference area for this study showed 9.85% damage and 6.81% loss for larger trees (>20 cm dbh), as well as 4.96% loss for smaller trees (<20 cm dbh) (Table 15). These differences between damage and loss in the previous study and the reference area of this study are likely because plots from Prengaman *et al.* (2008) included areas on lake-adjacent, east-facing slopes, which were more exposed to wind, as well as in the area of moderate damage immediately surrounding the microburst ("halo"). In contrast, the reference site plots for this study were chosen specifically so they would avoid slopes and the halo of damage around the microburst. In fact, five of the reference plots showed no damage from the hurricane at all.

The damage and loss values found by Prengaman *et al.* (2008) mentioned above are lower than those for the microburst area of this study for both large and small trees. The microburst area showed 66.4% damage and 50.8% loss for larger trees (>20 cm dbh) and 33.9% damage for smaller trees (<20 cm dbh) (Table 16). The higher rates of percent damage and loss in the microburst area compared to the damage found in the previous study can be explained by the intensity of the microburst disturbance.

Damage by size

This study used dbh as the measure of tree size, as it correlates with overall tree size (basal area, crown size) and is more straightforward to measure than tree height. Tree damage and loss increased with increasing size in this study, which is consistent with several other studies, whether they used dbh (Gresham *et al.* 1991, Everham and Brokaw 1996, Webb 1999, Peterson 2000b, Martin and Ogden 2006, Xi *et al.* 2008, Prengaman *et al.* 2008), or height as a measure of tree size (Foster 1988, Foster and Boose 1992).

Prengaman *et al.* (2008), whose study was also conducted in the College Woods, found that percent of total stems damaged increased with increased size, from 9.7% of stems smaller than 10 cm dbh to 32.4% of stems larger than 60 cm dbh. In the microburst area of this study, 32.3% of smaller stems (≥10 cm dbh) were damaged, while 94.3% of stems larger than 60 cm dbh were damaged (Table 16). Size class and percent damaged was correlated in the microburst area of this study, as well as size class and percent lost.

These results can be explained by several factors. As tree size increases, mass also increases, which can in turn increase strain on the root system (Putz *et al.* 1983). Larger trees also tend to have larger crowns, which not only increases weight (Runkle

1985) but also increases the amount of wind caught (Mergen 1954, Putz and Sharitz 1991, Putz *et al.* 1983, Quine and Gardiner 2007).

Loss in larger trees (canopy) was primarily by uprooting rather than breaking, while smaller trees are susceptible to secondary damage of crushing or breaking when larger nearby trees fall on them, as was also found by Webb (1989), Webb (1999), Xi *et al.* (2008), Prengaman *et al.* (2008), and Busing *et al.* (2009). Putz *et al.* (1983) had similar findings, with uprooted trees in general being larger, although some large trees also snapped, and with smaller trees snapping more often than they uproot (Putz *et al.* 1983, Everham and Brokaw 1996). Size class and percent uprooted was correlated in the microburst area of this study.

Damage by species

Quercus rubra sustained the highest basal area loss in both the microburst and reference areas. This agrees with the findings of Prengaman *et al.* (2008), who also found that *Q. rubra* suffered the highest percent of stems damaged (57.1%) and percent basal area loss (51.3%) of large species (≥20 cm dbh) in the College Woods. Busing *et al.* (2009) had similar results, with *Q. rubra* and *Q. velutina* showing the highest percent basal area loss in a North Carolina oak-hickory-pine forest. Greenberg and McNab (1998) found that *Q. rubra* and other red oaks (*Q. coccinea* and *Q. velutina*) uprooted more frequently than expected in a North Carolina forest. In their study involving experimental imitation of hurricane effects, Cooper-Ellis *et al.* (1999) found that *Q. rubra* uprooted 95% of the time (versus other damage such as trunk breaking) when pulled by a winch, and only 29% of damaged *Q. rubra* stems were still surviving after 6 years. In contrast, the smaller species *Acer rubrum* was uprooted, snapped, and bent at more equal frequencies (Cooper-Ellis *et al.* 1999).

Another *Quercus* species, *Quercus alba*, ranked third for percent basal area loss in the microburst area in this study (Table 8). Oaks tend to have large, branching crowns, which may be disadvantageous during a strong wind event. Previous studies have concluded that crown form may play more of a role in determining damage than dbh (Everham and Brokaw 1996, Prengaman *et al.* 2008). The large crown of *Q. alba* may make it more susceptible to damage from high speed winds, as seen in the microburst area of this study where this species had higher percent damage (71.43%) and percent basal area loss rates (75.05%) than for all species combined (64.98%). In contrast, Prengaman *et al.* (2008) found that *Q. alba* had lower percent stem damage (22.6%) and percent basal loss (12.7%) than the frequencies of damage and loss for all species combined for the College Woods (27.2% damage, 16.6% loss for all species combined), as well as lower rates than those for *Q. rubra* (57.1% damage, 51.3% loss). Also, the reference area of this study showed less damage and loss for *Q. alba* compared to *Q. rubra*. These results may indicate that *Q. alba* is more wind resistant than *Q. rubra* at lower wind speeds, perhaps due to a slower rate of growth (Burns and Honkala 1990, USDA NRCS 2002b).

Liriodendron tulipifera ranked second on the list of basal area loss by species in the microburst area (Table 8). *Liriodendron tulipifera* is a shade-intolerant, fast growing species, and may therefore have decreased wood strength. (Burns and Honkala 1990, USDA NRCS 2002a, Hart and Grissino-Mayer 2009). Previous studies indicate that pioneer species may be more susceptible to damage than late successional species (Everham and Brokaw 1996), because species that are early arrivers to a site tend to grow quickly, and therefore often have weaker wood (Peterson 2000a). Prengaman *et al.* (2008) found that *L. tulipifera* suffered less damage (12.5%) and loss (7.9%) in the College Woods than other species (27.2% damage, 16.6% loss for all species combined), and speculated that this was due to smaller crowns. *Liriodendron tulipifera* individuals had suffered damage during a previous ice storm in the region, which broke branches and therefore decreased crown size (Elstner and Ware 2001, Prengaman *et al.* 2008). However, these smaller crowns may not have been enough to avoid wind damage in this study due to the high windspeed in the microburst area.

The amount of damage and loss per species may also depend on size distribution of that species in a particular forest. Most *Quercus rubra* and *Liriodendron tulipifera* found in both the microburst and reference areas were large (dbh >55 cm). The median size of *Q. rubra* was 70 cm dbh, while that of *L. tulipifera* was 60 cm dbh. Conversely, species that suffered little to no damage were generally smaller in this particular forest, such as *Fagus grandifolia*. Previous studies suggest that susceptibility to damage may depend on if a species is predominantly found in the canopy or subcanopy (Martin and Ogden 2006, Prengaman *et al.* 2008). Although *F. grandifolia* suffered branch loss and crown damage during a previous ice storm (similar to *L. tulipifera* mentioned above), the fact that *F. grandifolia* individuals are shorter than much of the surrounding canopy also likely played a role in the decreased susceptibility to wind damage in the College Woods (Elstner and Ware 2001, Prengaman *et al.* 2008).

Among trees with individuals below 10 cm dbh, *Ilex opaca* showed less damage than expected in the microburst areas of this study (Table 12). *Ilex opaca* has previously shown resilience to hurricane damage (Batista and Platt 2003, Prengaman *et al.* 2008), likely due to its slow growth rate and tough wood (Burns and Honkala 1990). However, other species with individuals smaller than 10 cm dbh did show higher damage. *Cornus florida* sustained more loss and damage than expected in this size category based on the frequencies of damage and loss for all species combined. Similarly, Prengaman *et al.* (2008) also found that *C. florida* showed higher percent damage rate for small species (<20 cm dbh) than for all species combined in the College Woods. The loss and damage likely occurred when neighboring large trees were uprooted or lost branches, causing secondary damage to nearby smaller trees. Also, *C. florida* has shallow roots, which may increase vulnerability to damage when it is struck by a falling larger tree (Gresham *et al.* 1991, Peterson 2000a, USDA NRCS 2004).

Damage categories

In this study, smaller species were more likely to sustain damage from the bent, crush, and lean categories (Table 18). The damage in these categories is typically caused by secondary damage, which is covered in a later section. Because of their size relative to larger canopy trees, smaller trees are more likely to experience this secondary damage (Webb 1989, Prengaman *et al.* 2008). Cooper-Ellis *et al.*

(1999) found that *Acer rubrum*, an understory species, was more frequently crushed than uprooted in a simulated hurricane.

Uprooted and snapped off trees tended to be larger in this study, which is similar to previous studies (Cooper-Ellis *et al.* 1999, Prengaman *et al.* 2008). Foster (1988b) found that older stands were more likely to have uprooted and broken trees than younger stands. Also, a higher percentage of trees ≥10 cm dbh were uprooted or snapped off in the microburst area compared to the other damage categories. This is consistent with previous studies that found that uprooting was the most common form of damage caused by hurricanes (Greenberg and McNab 1998, Busing *et al.* 2009).

There were fewer standing individuals with broken branches in the microburst area of this study than might have been expected. This may be due to the high windspeeds in the microburst area, which may have been high enough to uproot trees before branches were lost. Branch loss can allow for increased tolerance to wind, as it reduces drag (Putz and Sharitz 1991).

Secondary damage

This study likely underestimates the amount of secondary damage that took place in the microburst area because secondary damage in large trees can be very difficult to distinguish from primary damage. Falling large trees can affect nearby large trees, breaking off branches or even causing them to uproot (Quine and Gardiner 2007). The ways a large tree causes the uprooting of another large tree are not always clear. The first tree may fall against the second tree with a great amount of force, which causes the root system to fail on the second tree. The first tree may also entangle its branches with the second tree, pulling the second tree down. The root systems of the two trees may also overlap, causing one to pull the other over (Prengaman *et al.* 2008). Also, when one tree falls, it may weaken the root systems of neighboring trees, although they do not actually fall until later in the storm (Everham and Brokaw 1996).

Sometimes, when large trees fall against other large trees, bark is skinned off of the second tree, which is easy to document. However, in many of the cases mentioned above, no evidence of secondary damage is left once both trees have landed on the ground. Branches and sometimes even the entire crown of a tree are broken up when the tree hits the ground, making any secondary damage difficult to recognize. While underestimating the amount of secondary damage would not likely have a large effect on the results, it could make a particular species seem more susceptible to wind damage or loss. For example, a tree could uproot due to proximity with a falling neighbor tree, and not because the species was particularly susceptible.

Sprouting of lost trees

When a tree snaps or uproots, it is usually considered "lost" from the forest (Prengaman *et al.* 2008). However, such a tree sometimes does not die, but rather sprouts. In fact, the ability of some species of trees to recover after wind damage may depend on their ability to resprout (Putz and Sharitz 1991). Also, when uprooted trees sprout, although they may not have advantageous positions in the canopy, they may have better established root systems than new seedlings (Putz *et al.* 1983). This may be one trade-off that allows species with weaker wood to recover after snapping (Putz *et al.* 1983). Previous studies indicate that sprouting occurs more frequently with snapped than uprooted trees, and may depend on water availability following the disturbance (Putz *et al.* 1983, Glitzenstein and Harcombe 1988). The ability to sprout also depends on the particular species, and large trees may sprout less than small trees (Putz *et al.* 1983, Everham and Brokaw 1996, Peterson 2000a).

In this study, most larger trees were uprooted rather than broken off, so there were few stumps and instead mostly trunks lying on the ground. Sixteen percent of uprooted trees sprouted (12 of 73) (Table 21). Putz *et al.* (1983) found that only 6% of uprooted trees sprouted (5 of 77). The higher percentage of sprouting in this study may be due to the fact that 5 of the 12 uprooted trees that sprouted were *Liriodendron tulipifera* individuals. The ability of this species to form stump sprouts is well known, and may help its ability recover from wind damage, as it is shade-intolerant and therefore needs to grow quickly to take advantage of new light gaps (USDA NRCS 2002). However, these were fallen trunks, not stumps and all sprouts on fallen *L. tulipifera* individuals in this study were dead five years after the hurricane.

Composition change

As recovery progresses, the microburst site will at least initially have a different composition and structure than the surrounding forest. The microburst site may be dominated by *Fagus grandifolia*, as many *F. grandifolia* individuals remained and many *Quercus* individuals were lost during the hurricane. Increased light availability in the microburst site may allow other shade intolerant species to establish. Busing *et al.* (2009) found that exotic species were able to establish themselves within the first 2 years following a disturbance. For example, during data collection for this study, several rapidly growing new *Paulownia tomentosa* saplings were found in the microburst site, ranging in size from 6.5 cm to 10 cm dbh. There may ultimately also be an increase in *Liriodendron tulipifera*, a shade-intolerant species (Harrington and Bluhm 2001). Many *L. tulipifera* seedlings have already established in the microburst area, likely due to increased light availability.

Although other species may enter the microburst site, the composition of this site may eventually return to what it was pre-disturbance. This may occur if seedlings of species already established in the site before disturbance successfully reach the canopy. Xi *et al.* (2008) found that 5 years following Hurricane Fran, the species make-up of a North Carolina forest had not significantly changed, apart from a few exotic species.

However, if species not already represented in the site are able to establish, the composition may remain different from pre-disturbance. Lang *et al.* (2009) found that 25 years after a wind disturbance in Wisconsin, the affected areas of the forest remained compositionally different from the pre-disturbance condition. Only time and resampling of permanent plots (including those established in this study) will answer the questions about the future composition of the College Woods.

Conclusions

In this study, the rank in abundance and basal area of species in the reference area was not the same as for the microburst area. Using the reference area as a substitute for the pre-disturbance composition of the microburst area would have produced inaccurate results. However, the forest was not salvage logged, which allowed for pre-disturbance composition reconstruction of the microburst area. This reconstruction was possible even three years after the hurricane, which is an argument for avoiding salvage logging in potential research areas.

Microburst winds cause more damage and loss in trees than general hurricane winds. The microburst area was considerably more damaged and lost more stems and basal area than the reference area. Larger trees were more susceptible to damage, loss, and uprooting caused by strong winds than smaller trees. Among large trees, *Quercus rubra* was the species with the highest frequency of damage and loss, which agreed with previous studies. *Quercus alba, Liriodendron tulipifera*, and *Oxydendron arboreum* also had high damage and loss frequencies for large trees, while *Ilex opaca* had low damage and loss frequencies and *Fagus grandifolia* had a low loss frequency. Among small trees, *Cornus florida* had high damage and loss frequencies, while *I. opaca* and *Liquidambar styraciflua* had low damage frequencies. The susceptibility of a species to a wind damage event may be related as much to the height of the majority of trees of that species at the time of the event as to the wood strength. The relatively shorter height of *F. grandifolia* individuals may have contributed to its low loss frequency even though this species is known to have brittle wood.

Susceptibility to damage and loss increases as tree size increases, especially with very strong winds. Large trees were more susceptible to uprooting and snapping off than small trees, while small trees were more susceptible to secondary damage caused by falling neighboring trees. Although some uprooted trees were able to resprout, these sprouts did not survive beyond five years and resprouting therefore will not contribute much to the future composition of this forest.

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